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Correlation between Battery Voltage under Loaded Condition and Estimated State of Charge at Valve-Regulated Lead Acid Battery on Discharge Condition using Open Circuit Voltage Method

Ahmad Qurthobi , Anggita Bayu Krisna Pambudi , Dudi Darmawan , and Reza Fauzi Iskandar

Department of Engineering Physics, School of Electrical Engineering, Telkom University, Indonesia

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ABSTRACT

One of the common methods that developed to predict state of charge is open circuit voltage (OCV) method. The problem which commonly occurs is to find the correction parameter between open circuit voltage and loaded voltage of the battery. In this research, correlation between state of charge measurement at loaded condition of a Panasonic LC-VA1212NA1, which is a valve-regulated lead acid (VRLA) battery, and open circuit voltage had been analyzed. Based on the results of research, correlation between battery's measured voltage under loaded condition and open circuit voltage could be approached by two linearization area. It caused by K_v's values tend to increase when measured voltage under loaded condition $V_M < 11.64$ volt. However, K_v values would be relatively stable for every $V_M \geq 11.64$ volts. Therefore, estimated state of charge value, in respect to loaded battery voltage, would increase slower on $V_M < 11.64$ volts and faster on other range.

Corresponding Author:
Ahmad Qurthobi
Department of Engineering Physics, School of Electrical Engineering, Telkom University
Jalan Telekomunikasi No 1 Terusan Buah Batu
+62-813-20262968
qurthobi@telkomuniversity.ac.id

1. INTRODUCTION

Lead acid battery is a type of dry elements. Its commonly used as energy backup storage for remote communities, telecommunication systems, or electric vehicles[1]-[4]. The problems which commonly occur on lead acid type batteries are overcharge and overdischarge. Both condition create temperature changes and physical deformation on the battery which affect on its performances. Therefore, it needs to analyzed battery's state of charge (SoC)[5]-[10].

State of charge (SoC) is a ratio between available and maximum electrical charge that stored in the battery[2],[11]. SoC is a non-dimentional unit and it could be expressed in percent or value between 0 and 1. SoC is an important parameter which not only to avoid harmful condition, such as overcharge and overdischarge, but also to expand the battery lifetime. One of the methods used to estimate state-of-charge is open circuit voltage (OCV). Statistically, correlation between state of charge and open circuit voltage could be represented as an linear equation. However, as loads attached to the battery, the loading effect would be occured. It would create gap between measured voltage and open circuit voltage[12]. Therefore, correlation between open circuit voltage and loaded battery voltage which culminated on their correlation with state of charge should be determined.

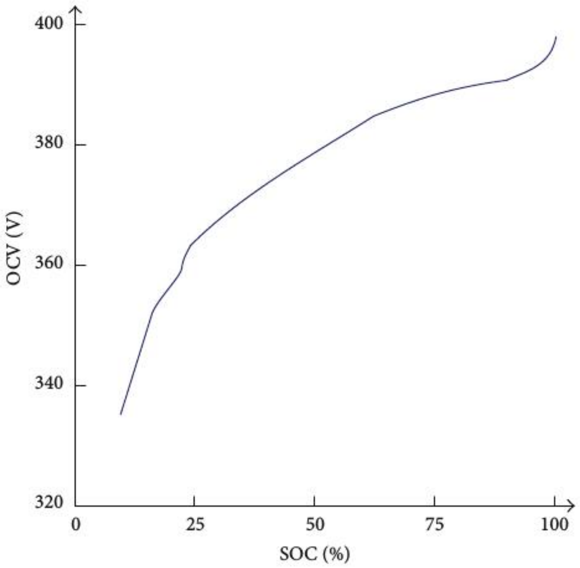


Figure 1. An example of typical correlation between state of charge and open circuit voltage[13]

In previous research, correlation between both variables in a Yuasa SWL2500 could be written as a constant value for several examination point[1]. Therefore, in this research, correlation between loaded battery voltage on discharge condition and open circuit voltage had been analyzed on a Panasonic LC-VA1212NA1, which is a valve-regulated lead acid (VRLA) battery. This research observes the changes of rest period parameter on the battery based on its loaded voltage at several points which leads to produce a precise estimation of state of charge.

2. RESEARCH METHOD

2.1. State of Charge and Open Circuit Voltage

As mentioned in section 1., state of charge or SoC is a non-dimentional unit which represents ratio between available and maximum charge stored in a battery. Hence, SoC is proportional to charge residues inside a battery and it could be represented as equation (1), where q_t and $q_{\max}$ represent, current and maximum charges values inside battery, respectively.

$$\text{SOC}_{\%} = \frac{q_t}{q_{\max}} \times 100 \tag{1}$$

On the real condition, neither zero point of a battery equal to zero charge ($q_0 \neq 0$) nor its maximum value equal to peak charge ($q_{\max} = q_{\text{peak}}$). The minimum and maximum charges values inside the battery are frequently mentioned by the manufacturers on battery's datasheet to keep its performances. Hence, equation (1) should be rewritten as equation (2), where $q_{\min}$ represents minimum charges value.

$$\text{SOC}_{\%} = \frac{q_t - q_{\min}}{q_{\max} - q_{\min}} \times 100 \tag{2}$$

There are some methods developed for SoC estimation. One of those estimation methods is open circuit voltage (OCV)[1]. OCV method has been developed based on an assumption that a battery is equal to a capacitor and the amount of charges (q) inside a capacitor is linearly proportional to its output voltage (V_t)(see equation (3)).

$$V_t = \frac{q_t}{C} \tag{3}$$

Statistically, if it is assumed that typical correlation between SoC and OCV is shown by figure 1, it could be approached by a linear formula such as equation (4)[13], where $V_{\min}$, α_1, and α_2 are, respectively, battery's minimum voltage (recommended by manufacturer), a multiplier constant, and a correction factor.

$$\text{SOC}_{\%} = \alpha_1 \times (V_t - V_{\min}) + \alpha_2 \tag{4}$$

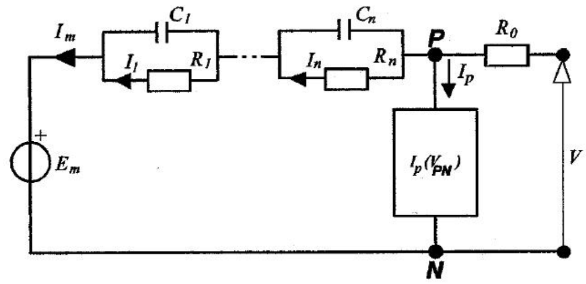


Figure 2. Lead acid equivalent network for both discharge and charge[12]

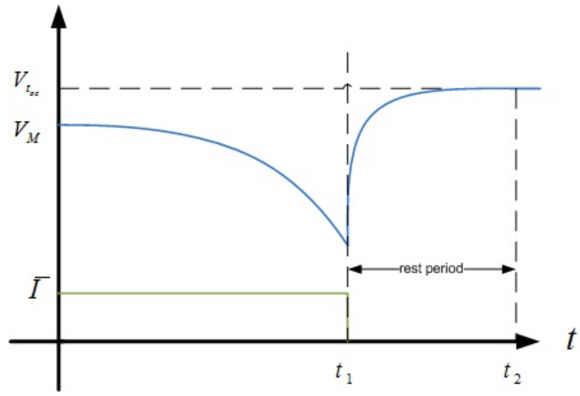


Figure 3. Typical voltage and current profile for a constant current discharge[12]

2.2. Battery Modelling and Rest Period

Equation (3) is only valid in specific conditions, such as when all of its loads are disconnected from the battery. However, removing loads from the battery for voltages examination creates a non-real time measurement. Barsali and Ceraolo(2002) define a lead acid battery's dynamic model to investigate its discharging dynamic behavior[12]. Lead acid equivalent network for charge and discharge are shown by figure (2). Furthermore, they also represent typical voltage and current profile for constant current discharge as shown on figure 3.

Figure 3 shows that there is exist a transition time required by the battery to show it open circuit voltage value after loads are removed. This transition time known as rest period [1],[2],[12]. Hence, OCV ($V_{t_{oc}}$) of a battery could be written as equation (5)[1], where V_M is measured voltage when loads are attached to the battery and K_v is a parameter derived from $V_{t_{oc}} - V_M$ after the battery is rested.

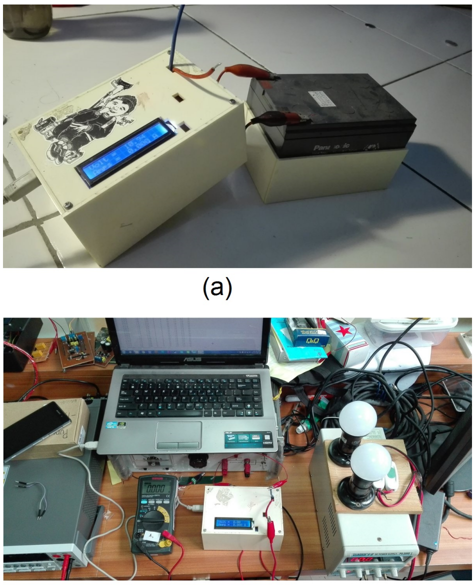
$$V_{t_{oc}} = V_M \pm K_v \tag{5}$$

2.3. Observing K_v

As mentioned in subsection 2.2., K_v is a parameter derived from differences between open circuit voltage and loaded voltage. It values could be varies on every point. Therefore, it needs to observe K_v values at several point to determine it correlation with battery's voltage. To determine the value of K_v at some specified point, a testing had beed done with this following steps:

1. As pre-conditioning process, a VRLA battery (Panasonic LC-VA1212NA1) has being charged until it reach its maximum voltage value recommended by its manufacturer, in this case is 13 volt[14](Figure 4(a)).

2. Connect the battery with a 10 watt load and measure its terminal voltagev(Figure 4(b)).



(a)

(b)

Figure 4. Battery charging and discharging process

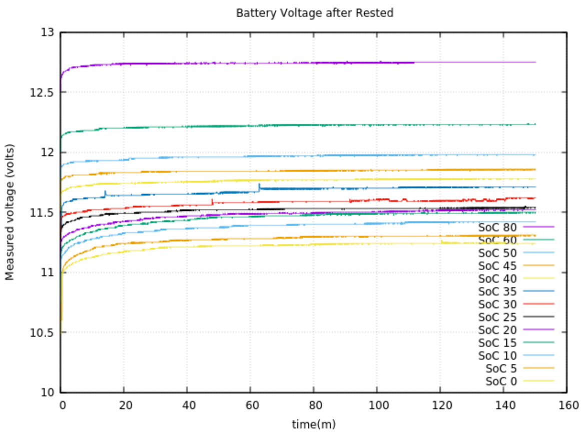


Figure 5. The changes of battery voltage measurement for 150 minutes

3. As soon when terminal voltage reach first point, remove load from battery and leave it rest for 150 minutes.
4. Monitor the change in battery voltage values, starting from the load released until the rest period ends.
5. Repeat step (2) to (4) for another monitoring point.

3. RESULT AND ANALYSIS

Figure 5 shows the change of experimental battery's voltage value when it rested for 150 minutes. This figure shows that loading effects which occurs on the battery results the measured voltage at loaded condition is lower than its open circuit voltage. The values are varies in range 0.22 - 0.74 volt.

Correlation between measured voltage under loaded condition V_M and open circuit voltage V_{oc} after rest period on the battery are shown in figure 6. It informs the gradient of correlation curve of V_M and V_{oc} for $V_M \geq 11.64$ volt is relatively constant with $\frac{\partial V_{oc}}{\partial V_M} \approx 1$ with small zero offset addition. However, for

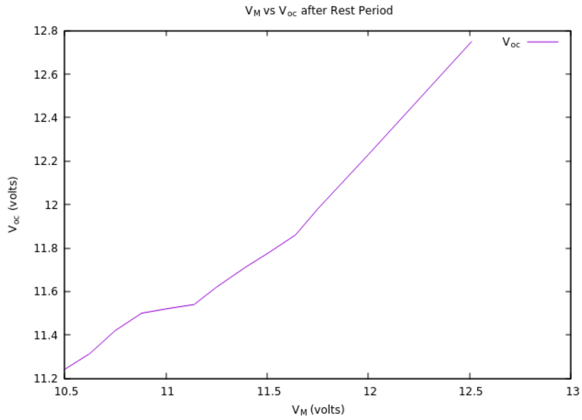


Figure 6. Correlation between measured voltage V_M under loaded condition and open circuit voltage V_{oc} after 150 minutes of rest period

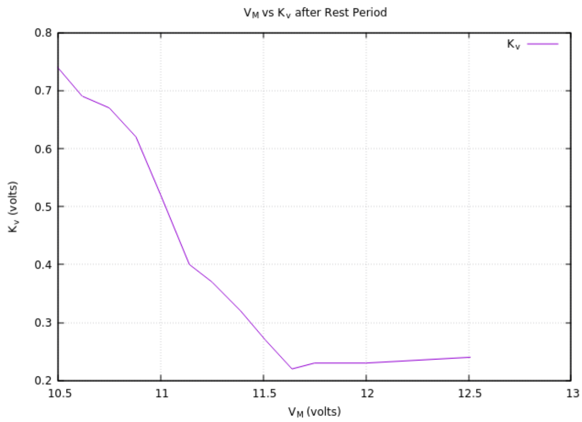


Figure 7. Correlation between measured voltage V_M under loaded condition and correction parameter K_v

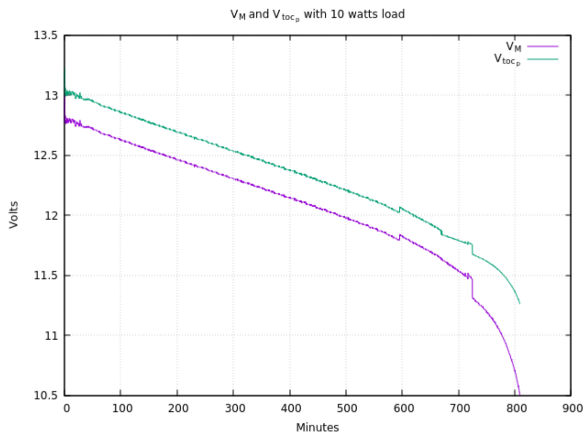


Figure 8. Measured voltage under loaded condition and estimated open circuit voltage in respect to time

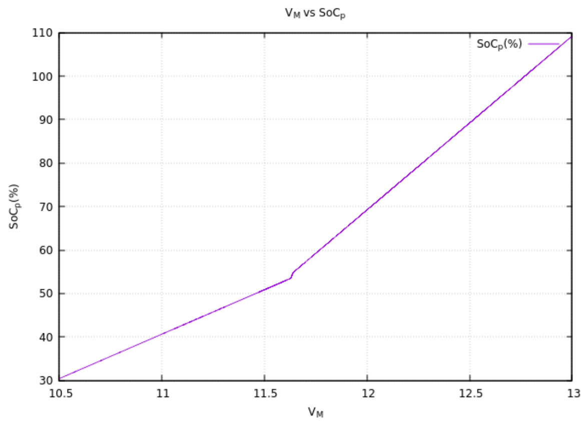


Figure 9. Correlation between V_M and SOC$_p(\%)$

$V_M < 11.64$, correlation between both variable relatively fluctuative and could be approached by equation (6).

$$V_{oc} = 0.50V_M + 6.02 \tag{6}$$

This condition yeilds correlation between K_v and V_M had negative gradient for every $V_M < 11.64$ volts. In the other hand, it is relatively stable with average $K_v = 0.23$ volt for $V_M \geq 11.64$ volts (see figure 7). Hence, evolution ov K_v could be devided into two linearization condition and could be written as equation(7).

$$K_v = \begin{cases} -0.49V_M + 5.90; & \text{for } V_M < 11.64 \\ 0.23; & \text{for others} \end{cases} \tag{7}$$

However, the result shows different outcome with another research with another VRLA battery, where K_v values are almost constant for every inspection points(80%, 60%, 40%, and 20% of SoC) on Yuasa SWL2500 battery with 240 minutes of rest period[1].

Based on equation (5) and (7), correlation between measured loaded voltage and estimated open circuit voltage value in respect to time could be drawn as figure 8. As results of implementation of K_v values, the gap between both curves would increase as soon as measured voltage under loaded condition is less than 11.64 volts. Therefore, correlation between state of charge and V_M could be shown as figure 9 and could be written as equation (8).

$$\text{SoC}_{\%} = \begin{cases} 20.44V_M - 184.64; & \text{for } V_M < 11.64 \\ 40V_M + 410.8; & \text{for others} \end{cases} \tag{8}$$

As validation process, testing on subsection 2.3. had been repeated with addition of new examination point at $V_M = 12.24$ volts. Figure 10 shows correlation between estimated open circuit voltage V_{toc_p} and actual voltage V_{real}. This figure shows correlation between both variables could be approached with a linear formula and could be written as equation (9). It also informs the average absolute error between V_{toc_p} and V_{real} is 0.02 volt.

$$V_{\text{real}} = 1.02V_{toc_p} + 0.28 \tag{9}$$

4. CONCLUSION

Based on the results of research, correlation between battery's measured voltage under loaded condition and open circuit voltage could be approached by two linearization area. It caused by K_v's values tend to increase when measured voltage $V_M < 11.64$ volt and correlation between both variables could be written as $-0.49V_M + 5.90$ volt. However, K_v values would be relatively stable on 0.23 volt for every $V_M \geq 11.64$ volts. Therefore, in respect to loaded battery voltage, estimated state of charge value would increase slower on $V_M < 11.64$ volts and faster on other range. It shows different outcome with another research with another VRLA battery, where K_v values are almost constant for four inspection points(80%, 60%, 40%, and 20% of SoC) on Yuasa SWL2500 battery with 240 minutes of rest period.

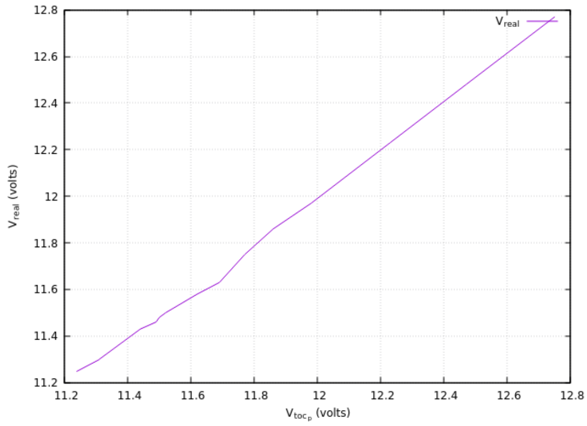


Figure 10. Correlation between V_{toc_p} and V_{real}

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BIOGRAPHIES OF AUTHORS

Ahmad Qurthobi is a lecturer and researcher at Department of Engineeering Physics, School of Electrical Engineeering, Telkom University (2013-present). He obtained Bachelor Degree in Telecommunication Engineering from STT Telkom (Indonesia) in 2007 and Master Degree in instrumentation and Control from Institut Teknologi Bandung (Indonesia) at 2011.
His researches are in fields of electric power, instrumentation, control system, renewable energy, and power electronics.
He is affiliated with PII as member.
For further info on his homepage: http://qurthobi.staff.telkomuniversity.ac.id/

Anggita Bayu Kresna Pambudi is an engineer of National Electric Company of Indonesia. He obtained Bachelor Degree in Engineering Physics from Telkom University (Indonesia) at 2016.
His researches are in fields of instrumentation, and measurement.
Beside his activity as engineer, he also runs a start up design company called Dodlezig.
For further info on his homepage: http://www.anggitabay.com/

Dudi Darmawan is a lecturer and researcher at Department of Engineeering Physics, School of Electrical Engineeering, Telkom University (1999-present). He obtained Bachelor Degree in Physics in 1998, Master Degree in instrumentation and Control at 2004, and Doctoral Degree in Engineeering Physics at 2015 from Institut Teknologi Bandung(Indonesia).
His researches are in fields of non-destructive testing, instrumentation, tomography, and electromagnetics.
For further info on his homepage: http://dudiddw.staff.telkomuniversity.ac.id/

Reza Fauzi Iskandar is a lecturer and researcher at Department of Engineeering Physics, School of Electrical Engineeering, Telkom University (2012-present). He obtained Bachelor Degree in Physics Education from Universitas Pendidikan Indonesia at 2003, and Master Degree in instrumentation and Control from Institut Teknologi Bandung (Indonesia) at 2011.
His researches are in fields of instrumentation, control system, power electronics, and renewable energy.
For further info on his homepage: http://rezafauzii.staff.telkomuniversity.ac.id/